Materials for Harsh Service Conditions: Technology Assessment

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1. Introduction to the Technology/System

1.1 Overview of Materials for Harsh Service Conditions

The physical limitations of materials in demanding environments have long constrained engineers in the design of innovative new products and technologies. Aggressive service environments can involve high temperatures, high pressures, corrosive chemicals, mechanical wear, neutron irradiation, and hydrogen attack. These aggressive environments—and the associated materials durability challenges—are common across multiple applications and sectors. New materials solutions are needed to meet stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits. As a few examples:

- Gas and steam turbine power plants could achieve higher efficiencies if they operated at higher inlet temperatures, but operating temperatures are constrained by the thermal stability of existing turbine alloys at high temperatures and pressures. Gas, steam, and combined cycle turbine power plants in the U.S. electric power sector collectively generate about 1,800 million megawatt hours (6 Quads) of electricity annually,[1] comprising about 46% of the country's total electricity production.[2]
- Waste heat recovery can provide major efficiency gains at manufacturing sites, but many sources of industrial waste heat are currently unrecoverable because recuperator alloys are incompatible with corrosive, high-temperature flue gases. Process heating across the manufacturing sector alone consumes over 7 Quads of energy.[3]
- Corrosion of iron and steel pipelines can cause leaking of natural gas into the environment, leading to wasted energy, explosion hazards, and methane emissions. Pipeline corrosion has accounted for over 1,000 significant pipeline incidents over the past 20 years, directly resulting in 23 fatalities and over $822 million in property damage.[4]
- Magnesium and other lightweight structural metals could significantly reduce the weight of vehicles for better fuel economy and lower emissions: a 10% reduction in vehicle mass can yield a 6% increase in fuel economy.[5] However, the use of lightweight metals in automobiles is limited by their resistance to corrosion and durability in high-friction environments.
- Conventional nuclear fuel cladding materials are unstable at very high temperatures and can contribute to nuclear core meltdowns in loss-of-coolant accidents.[6] Safer, irradiation-resistant and phase-stable nuclear fuel cladding materials could mitigate Fukushima-like disasters at nuclear facilities.

1.2 Challenges and Opportunities

Research needs can be roughly divided into three cross-cutting materials challenges. **Phase-stable materials** are needed for applications requiring material stability in extreme environments, such as ultra-high pressure or ultra-high temperature. Research in **functional surfaces** is needed to develop advanced coatings and surface treatments that provide outstanding material properties at surfaces, such as corrosion and wear resistance. Embrittlement-resistant materials are needed to resist **material**

[1] Total generation for steam, gas, and combined cycle turbines was calculated by assuming that these prime movers contribute 72% of all coal, oil, and natural gas electricity generation. The 72% ratio was calculated from the breakdown of capacities by prime mover as reported in 2012 EIA-860 survey data (http://www.eia.gov/electricity/data/eia860/). Total electricity production by fuel type was drawn from Annual Energy Outlook data (http://www.eia.gov/forecasts/aeo/data.cfm#summary).

[2] *Annual Energy Outlook 2014, Reference Case Data*

[3] "Manufacturing Energy and Carbon Footprint: All Manufacturing (NAICS 31-33)", U.S. DOE Advanced Manufacturing Office (2014).

[4] Data from "Significant Incident 20 Year Trend" (2014), US DOT Pipeline and Hazardous Materials Safety Administration (https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?Portalpages&NQUser=PDM_WEB_USER&NQPassword=Public_Web_User1&PortalPath=%2Fshared%2FPDM%20Public%20Website%2F_portal%2FSC%20Incident%20Trend&Page=Significant)

[5] *Linking Transformational Materials and Processing for an Energy-Efficient and Low-Carbon Economy: Creating the Vision and Accelerating Realization – Opportunity Analysis for Materials Science and Engineering.* The Minerals, Metals, and Materials Society (2012) (http://energy.tms.org/docs/pdfs/Opportunity_Analysis_for_MSE.pdf)

[6] P. Hofmann, S. Hagen, G. Schanz, and A. Skokan, "Chemical Interaction of Reactor Core Materials Up to Very High Temperatures," Kernforschungszentrum Karlsruhe Report No. 4485 (1989).

aging effects in certain extreme environments, including exposure to hydrogen (which can cause hydrogen embrittlement) and radiation (which can cause neutron embrittlement and radiation-induced swelling). Example applications within these three major research areas are illustrated in Figure 1.

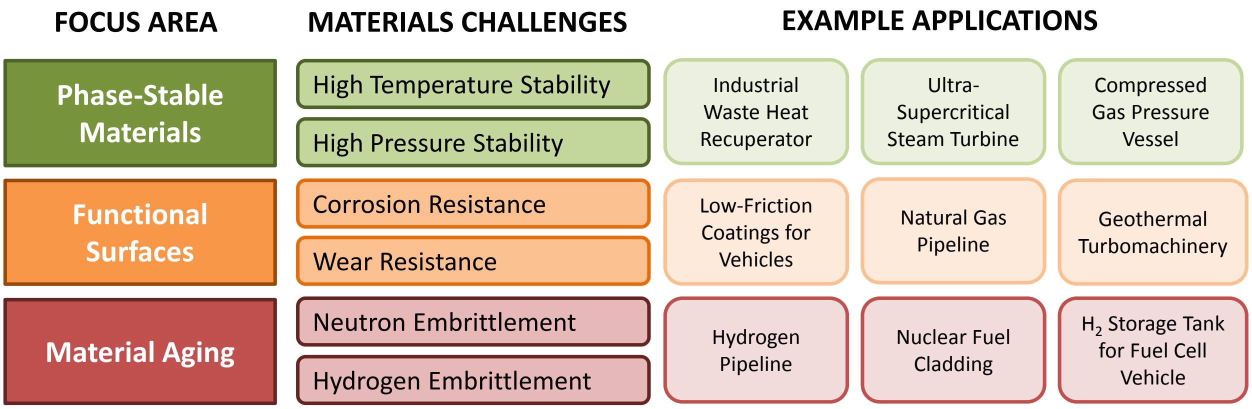

Figure 1. Major research areas include phase-stable materials, functional surfaces, and embrittlement-resistant materials. Within each cross-cutting area, numerous clean energy applications provide opportunities for energy savings and emissions reductions.

1.3 Public and Private R&D Activities

A representative list of ongoing public and private research activities related to durable materials are detailed in Table 1. A common link between programs is that they are generally application-focused: research is initiated and carried out with an aim to solve a particular problem. This focused approach fails to recognize that many materials challenges are shared by many applications, and programs may have substantial overlap. A gap in current public and private research activities is a convening power to unify research under the durable materials umbrella, which could provide tremendous new opportunities for collaboration.

Table 1. Ongoing public and private R&D programs in key application areas for materials in harsh environments

Application	Significant Programs	R&D Focus Areas
High-temperature materials for gas and steam turbines	• DOE Clean Coal Plant Optimization Technologies Program • EPRI Fossil Fleet for Tomorrow Program • EPRI Fossil Materials and Repair Program	The DOE Clean Coal Plant Optimization Technologies Program includes R&D on high-temperature turbine alloys in its focus. EPRI programs are conducting research on corrosion, fabrication methods, and joining techniques for advanced ferritic and austentitic alloys.
Durable nuclear fuel cladding materials	• DOE Light Water Reactor Sustainability Program • EPRI Long-Term Operations Program	The DOE Light Water Reactor Sustainability Program includes cladding research as a subtopic within the "Advanced Light-Water Reactor Nuclear Fuels" R&D pathway.
Materials for waste heat recovery in harsh environments	• Oak Ridge National Laboratory (ORNL)/Gas Technology Institute (GTI) project: "Advanced Energy and Water Recovery Technology from Low Grade Waste Heat"	Research in the DOE Advanced Manufacturing Office includes as a focus "innovative waste-heat recovery to improve sustainability, reduce water usage, and decrease the energy footprint of U.S. manufacturing."
Corrosion- and embrittlement-resistant materials	• DOE Hydrogen and Fuel Cells Program • NIST Hydrogen Pipeline Material Testing Facility	Related research is underway at the National Center for Hydrogen Technology (NCHT), NIST, and the DOE Hydrogen and Fuel Cells Program, but no program

Application	Significant Programs	R&D Focus Areas
for gas pipeline infrastructure	• NIST Pipeline Safety Program • Energy & Environmental Research Center's National Center for Hydrogen Technology	ties together durability issues for natural gas and hydrogen pipelines. This could be especially important to enable a shared hydrogen/natural gas pipeline infrastructure (mixed-gas pipelines).
Coatings and surface treatments for lightweight metals in vehicles	• DOE Vehicle Technologies Office: Materials Technologies • Lightweight and Modern Metals Manufacturing Innovation (LM3I) Institute • ORNL Carbon Fiber Technology Facility (CFTF) • Army Research Laboratory: Coatings Team	Academic and industry researchers are currently developing anticorrosion coatings for lightweight Al and Mg alloys. The Army Research Lab is performing research on corrosion-resistant coatings for vehicles, munitions, and other equipment. The new Lightweight and Modern Metals Manufacturing Innovation Institute will focus on manufacturing and scale-up of innovative lightweight alloys.
Corrosion-resistant materials for geothermal applications	• DOE Geothermal Technologies Office • Frontier Observatory for Research in Geothermal Energy (FORGE)	No major government research programs are investigating corrosion-resistant geothermal turbomachinery,[7] but a U.S. start-up company showcased at the 2014 DOE National Clean Energy Business Plan Competition is now developing corrosion-resistant, low-cost carbon fiber turbocompressors.[8]

2. Technology Assessment and Potential

Considering the broad cross-sector applicability of durable materials, it is not possible to identify and sum every current and future energy-savings opportunity in this area. Instead, a "case study" approach was used to identify the opportunity space and potential benefits for important known applications. Impacts for six applications are explored in this section.

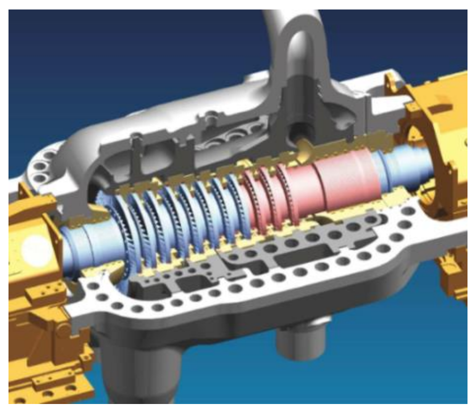

Figure 2. Schematic of an advanced ultra-supercritical steam turbine with 1400°C superalloy inlet (GE Power & Water)[13]

2.1 Gas and Steam Turbines

Gas, steam, and combined cycle turbine power plants in the U.S. consume an estimated 16.7 Quads of primary energy to produce 6.2 Quads of electricity output.[9] These power plants account for a disproportionally large portion of the electric power industry's emissions, with 1.7 billion tons of greenhouse gases (CO_2-equivalent) released into the environment annually from coal-fired plants alone.[10] The

[7] Steam-jet injectors, not turbocompressors, are conventionally used to remove non-condensable gases from geothermal steam.

[8] "Black Pine Engineering Wins Clean Energy Trust Clean Energy Challenge," DOE Office of Energy Efficiency & Renewable Energy (2014), http://energy.gov/eere/articles/black-pine-engineering-wins-clean-energy-trust-clean-energy-challenge

[9] Source for average fleet efficiency: "U.S. Electricity Flow," EIA, 2013 (http://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf). Total generation for steam, gas, and combined cycle turbines was calculated by assuming that these prime movers contribute 72% of all coal, oil, and natural gas electricity generation. The 72% ratio was calculated from the breakdown of capacities by prime mover as reported in 2012 EIA-860 survey data (http://www.eia.gov/electricity/data/eia860/). Total electricity production by fuel type was drawn from Annual Energy Outlook data (http://www.eia.gov/forecasts/aeo/data.cfm#summary).

[10] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012,* U.S. Environmental Protection Agency (2014).

majority of U.S. gas and steam turbine power plants operate in the subcritical regime, resulting in an overall fleet average efficiency of just 37%.[11] Advanced ultra-supercritical steam turbines operating at 1300°F and above, shown schematically in Figure 2, could boost efficiencies of steam turbines beyond 50%.[12] Combined cycle power plants—which utilize both a gas and steam turbine working from the same source of heat for increased efficiency—can reach even higher efficiencies.[13] The relationship between operating conditions, typical net plant efficiency, and net plant heat rate is shown in **Table 2** for coal-fired plants.

Table 2. Relationship between operating conditions, plant efficiency, and heat rate for coal-fired power plants. Data source: Viswanathan, *et al.* 2010.[14]

Operating Regime	**Typical Conditions**		**Net Plant Efficiency (%)**	**Net Plant Heat Rate***
	Temperature (Main Steam)	Pressure		
Subcritical	<1000°F	2400 psi	35%	9,751 Btu/kWh
Supercritical	1050°F	3600 psi	38%	8,981 Btu/kWh
Ultrasupercritical	1100°F	4200 psi	>42%	8,126 Btu/kWh
Advanced Ultrasupercritical	>1300°F	5000 psi	>45%	7,757 Btu/kWh

*Net plant heat rate calculated on the basis of fuel higher heating value (HHV).

Ultimately, turbine efficiencies are thermodynamically limited by their upper operating temperature. As the temperature increases, so does the efficiency envelope—and typically, this also means an increase in the efficiency that can be achieved in practice. The relationship between operating efficiency and operating temperature is shown in Figure 3 for several actual power plants and commercial turbines.

[11] "U.S. Electricity Flow," EIA, 2013.
[12] *Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation*, International Energy Agency (2012).
[13] State-of-the-art combined cycle plants can now exceed 60% efficiency, but continue to be limited by the temperature stability of available turbine alloy materials. See: "Efficiency Record of Combined Cycle Power Plant," Siemens Innovation News (2011)
[14] R. Viswanathan, J. Shingledecker, and R. Purgert, "Evaluating Materials Technology for Advanced Ultrasupercritical Coal-Fired Plants," Power, 8/1/2010, available from: http://www.powermag.com/evaluating-materials-technology-for-advanced-ultrasupercritical-coal-fired-plants/

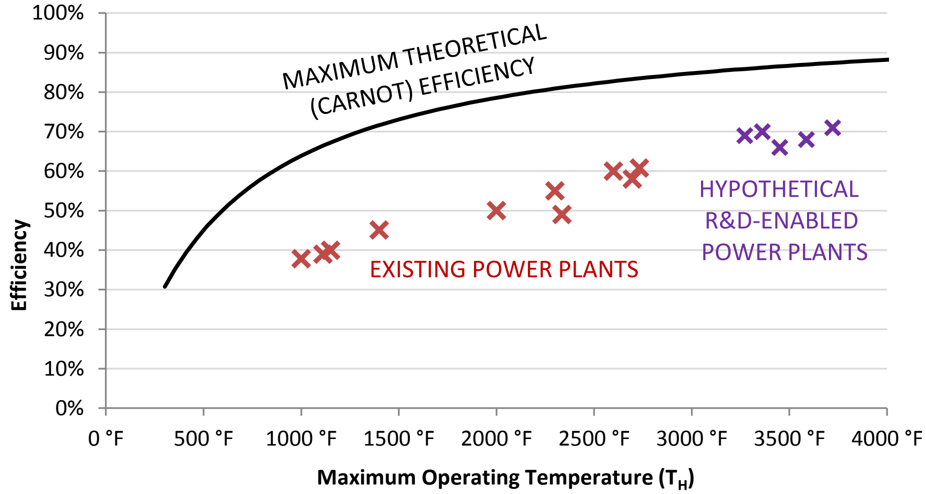

Figure 3 Efficiency vs. operating temperature for existing and hypothetical gas/steam turbine power plants and commercial turbines,[15] and the maximum theoretical efficiency for heat engines operating in the same temperature ranges. Ambient assumed to be 20°C.

Materials research could boost efficiencies by expanding the theoretical envelope, as illustrated by the hypothetical power plants shown in purple. Further R&D is needed to qualify materials with the following minimum characteristics:

- Temperature stability exceeding 1300°F at 5000 psi pressure;
- Minimum 100,000 hour rupture strength of 14,500 psi at the operating temperature;[16]
- Steamside oxidation and erosion resistance over component lifetime;
- High-temperature fireside corrosion resistance to gas mixtures containing deposits of coal; and
- Fabricability, including ability to press-form, machine, and weld material.

Key advantages and disadvantages of the three main material classes under development for advanced supercritical turbines (ferritic steel, austentitic steel, and nickel alloys) are summarized in **Table 3**.

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[15] Existing plants/commercial turbines included in chart: Belews Creek Power Station (538°C / 37.8% eff.); John W Turk Power Plant (600°C / 39.0% eff.); Philo 6 Power Plant (621°C / 40.0% eff.); Dan River Station Unit 3 (760°C / 45.1% eff.); GE E-Class Turbine (1093°C / 50.0% eff.); GE F-Class Turbine (1260°C / 55.0% eff.); Yokohama Station (1280°C / 49.0% eff.); GE H-Class Turbine (1426°C / 60.0% eff.); West County Energy Center (1480°C / 58.0% eff.); and Irsching Power Plant (1500°C / 60.8% eff.).

[16] R. Viswanathan, J. Shingledecker, and R. Purgert, "Evaluating Materials Technology for Advanced Ultrasupercritical Coal-Fired Plants," Power, 8/1/2010, available from: http://www.powermag.com/evaluating-materials-technology-for-advanced-ultrasupercritical-coal-fired-plants/

Table 3. Advantages and disadvantages of advanced ultrasupercritical alloys. Source: Viswanathan, *et al.* 2010.[17]

Material	Example Alloys	Maximum Operating Temperature (at 5000 psi)	Advantages	Disadvantages	Possible Applications in an Ultrasupercritical Turbine
Ferritic Steels	SAVE12, NF12, VM12, MARB2	650° – 650° F	High strength at low-end temperatures; low cost; can be welded readily	Low temperature resistance and sensitive to oxidation, but could be used in some applications with protective coatings	Low-temperature components such as furnace tubing/piping
Austentitic Steels	Super 304H, HR3C, T92, T22	1,000° – 1,270° F	High strength at intermediate temperatures; low cost; can be welded readily	Sensitive to oxidation; low conductivity; high thermal expansion; not suitable for thick-section applications	Mid-temperature applications, including superheater and reheater tubes
Nickel-based alloys	Haynes 230, Inconel 617, Haynes 740, HR6W	1,370° – 1,460° F	High temperature compatibility; high oxidation resistance	Very high cost; not all alloys are code approved, so extensive testing required	Highest temperature, highest stress components, such as heavy-wall piping

Overall, more-efficient power plants resulting from advanced high-temperature materials could provide energy savings exceeding 1 Quad in the US. It is projected that over 200 GW of summer capacity will be added to the U.S. electric-generating fleet in the form of steam, gas, and combined cycle power plants by 2040, providing an estimated 3.6 Quads of annual electricity generation.[18] **Table 4** shows the potential energy and emissions savings[19] for efficiency improvements in these projected new additions only.

Table 4. Annual energy and emissions savings opportunities for efficiency improvements in new power plants added by 2040, measured from baseline efficiencies of 37% (the current U.S. fleet average) and 60% (the current state of art).

Opportunity Resulting from Durable Materials R&D	Energy and Emissions Savings from Current Fleet Average (37%)			Energy and Emissions Savings from State-of-Art Combined Cycle (60%)		
	Power Plant Efficiency	Energy Savings	Emissions Savings	Power Plant Efficiency	Energy Savings	Emissions Savings
Efficiency gains of 1%	38%	257 TBtu	26.4 million tons CO_2	61%	99 TBtu	10.1 million tons CO_2
Efficiency gains of 5%	42%	1,161 TBtu	119.2 million tons CO_2	65%	463 TBtu	47.5 million tons CO_2
Efficiency gains of 10%	48%	2,076 TBtu	213.1 million tons CO_2	70%	859 TBtu	88.2 million tons CO_2
Efficiency gains of 15%	52%	2,814 TBtu	288.9 million tons CO_2	75%	1,203 TBtu	123.5 million tons CO_2

[17] R. Viswanathan, J. Shingledecker, and R. Purgert, "Evaluating Materials Technology for Advanced Ultrasupercritical Coal-Fired Plants," Power, 8/1/2010, available from: http://www.powermag.com/evaluating-materials-technology-for-advanced-ultrasupercritical-coal-fired-plants/

[18] Unpublished analysis by Energetics Incorporated based on 2014 Annual Energy Outlook (AEO) projections.

[19] Emissions savings based on an emissions factor of 205.3 pounds CO2 per million Btu of input energy (for bituminous coal). Data source: http://www.eia.gov/electricity/annual/html/epa_a_03.html

2.1 Waste Heat Recovery

In 2012, the U.S. industrial sector consumed 30.5 Quads of primary energy—31% of U.S. primary energy consumption.[20] Roughly one-third of industrial energy use is released as waste heat, and recovery of this excess thermal energy offers substantial opportunities for energy savings and emissions reductions for industrial facilities.[21] Waste heat can be recycled either by redirecting the waste stream for use in other thermal processes (e.g., flue gases from a furnace could be used to pre-heat a lower-temperature drying oven) or by converting the waste heat to electricity in a process called waste heat-to-power (WHP). According to EIA Manufacturing Energy Consumption Survey data, only about 6% of U.S. manufacturing facilities were using any type of waste heat recovery as of 2010.[22] Among the energy-intensive industries (chemicals, petroleum refining, primary metals, food, and paper products), average usage was somewhat higher, with 13% of facilities using waste heat recovery—but reported use is still low overall.

Opportunities for waste heat recovered are analyzed in greater detail in a separate Technology Assessment [Waste Heat Recovery TA], but it is worth noting here the challenges in recovering waste heat in harsh industrial environments. Many medium- to high-temperature waste streams are contaminated with corrosive chemicals or particulate matter. Heat recovery is often not possible for contaminated heat sources because heat exchanger materials are not available with adequate resistance to corrosion, oxidation, and fouling, processes which are accelerated at high temperatures.[23] Furthermore, materials that are suitable for use at temperatures above 1200°F, where the highest energy gains are possible, are costly. There is a strong need for durable, low-cost alloys for heat exchanger systems. Industries with high potential for energy savings through waste heat recovery in harsh environments include the steel, glass, aluminum, and cement/lime industries. The estimated recoverable energy from high-temperature and corrosive waste heat streams in these industries is estimated to be over 0.3 Quads annually, as shown in Table **5**. Corresponding emissions reductions from reduced demand for fossil fuels total 14.5 million tons of CO_2 avoided. [24]

Table 5. Estimated recoverable energy from corrosive and high-temperature industrial waste heat sources[25]

Industry	Waste Heat Sources	Waste Heat Stream Characteristics	Temperature Range	Technology Challenges	Annual Recoverable Potential*
Steel	Blast furnace	Contains combustibles and particulates	750–1112°F	Blast furnace pressures are typically too low for top gas pressure recovery. Contaminated wastewater produced during chemical energy recovery present disposal challenges. Recuperator corrosion from particulate content in exhaust gas is an issue.	188 TBtu/yr

[20] *Annual Energy Outlook 2014: Reference Case Data,* U.S. Energy Information Administration (2014).
[21] T. Hendricks and W. T. Choate, "Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery," U.S. Department of Energy Industrial Technologies Program (2006).
[22] *Number of Establishments by Usage of General Energy-Saving Technologies, 2010,* Energy Information Administration (2013).
[23] *Waste Heat Recovery: Technology and Opportunities in U.S. Industry*, U.S. Department of Energy Industrial Technologies Program (2008).
[24] Assuming 117.1 lbs of emitted CO_2 per million Btu of natural gas used (EIA, Carbon Dioxide Uncontrolled Emission Factors, http://www.eia.gov/electricity/annual/html/epa_a_03.html), a reduction of 247 TBtu energy corresponds to a reduction of 28,924 million pounds (14.5 million tons) of CO_2 released.
[25] Data Source: S. Nimbalkar, A. C. Thekdi, B. M. Rogers, O. L. Kafka, T. J. Wenning, "Technologies and Materials for Recovering Waste Heat in Harsh Environments," Oak Ridge National Laboratory (2015), *to be published.*

Industry	Waste Heat Sources	Waste Heat Stream Characteristics	Temperature Range	Technology Challenges	Annual Recoverable Potential*
	Electric arc furnace	Contains combustibles and particulates; variable gas flow	2730–2910°F	Exhaust gases can be used to preheat scrap, but process control is challenging due to variable flow rates, exhaust gas temperature cycling, and flammable contaminants in the scrap. Toxic compounds can form during scrap preheating, raising safety issues.	62 TBtu/yr
	Basic oxygen processes	Contains combustibles and particulates; variable gas flow	2280–3090°F	Combustible volatiles present in gases can lead to undesired temperature increases and reactions with constituents of heat exchanger equipment.	30 TBtu/yr
Glass	Glass furnace	Contains particulates and condensable vapors	810–2610°F	Regenerators are widely used for primary heat recovery, but unrecovered heat remains significant. Batch/cullet preheating is limited by cleanliness of available cullet. Electric power generation from primary heat recovery unit has not been demonstrated for gases containing particulates.	43 TBtu/yr
Aluminum	Aluminum melting furnace	Contains combustibles and particulates	1380–1740°F	Combustion air preheating systems are frequently used in the US, but maintenance costs are very high due to corrosion and fouling. Metallic tube heat exchangers can have a lifetime of as little as 6-9 months. Overheating of systems is possible due to combustible content in flue gases.	16 TBtu/yr
	Anode baking	Contains combustibles, particulates, and organic matter	570–930°F	Technology not yet demonstrated; corrosion, fouling, and overheating are known issues.	2 TBtu/yr
Cement / Lime	Cement kiln (clinker)	Contains particulates, but relatively easy to handle	390–750°F	Waste heat is widely used in new plants to preheat charge material, although use increases maintenance costs and retrofitting is difficult for older plants. Thermoelectric generation has not been demonstrated, and must overcome short performance life, low efficiency, and contamination issues. Clinker cooling air heat recovery is commonly used, but can affect product quality and may not be available for small kilns.	53 TBtu/yr
	Lime kiln (rotary)	Contains particulates, but relatively easy to handle	390–1110°F	Waste heat is widely used in new plants to preheat charge material, although use increases maintenance costs and can generate excess dust. Costs generally cannot be justified for smaller facilities and retrofits. Regenerators are available, but fouling can be an issue.	41 TBtu/yr
Total					**247 TBtu/yr**

* Includes a small amount of waste heat that is already being recovered using existing waste heat recovery technologies.

2.2 Gas Pipeline Infrastructure

Over 2.1 million miles of natural gas pipelines serve the U.S.,[26] delivering 24 trillion cubic feet (equivalent to 25 Quads) of natural gas to consumers annually.[27] About 40% of U.S. pipelines date from

[26] *Annual Report Mileage for Gas Distribution Systems*, Pipeline & Hazardous Materials Safety Administration (2014).
[27] *Natural Gas Summary*, U.S. Energy Information Administration, available from: http://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm

the 1960's or earlier, before the first pipeline safety regulations.[28,29] In an aging fleet, pipeline corrosion has emerged as a significant safety issue; corrosion has accounted for over 1,000 significant pipeline incidents over the past 20 years, directly resulting in 23 fatalities and over $822 million in property damage.[30] Older pipelines manufactured from cast or wrought iron are the most susceptible to corrosion and leaks. These materials are especially common in urban areas, where it is difficult to access and replace gas mains. In a recent study, U.S. researchers surveyed the streets of Washington, DC for natural gas leaks and found nearly 6,000 leaks beneath 1,500 miles of roadway—an average of four leaks per mile.[31] Fugitive emissions from U.S. pipelines are responsible for the release of 1.1 million tons of methane gas annually into the environment (28.6 million tons CO_2 equivalent).[32]

Modern pipelines are protected from external corrosion (from the soil or water surrounding the pipeline) through anti-corrosion coatings and cathodic protection. However, most pipelines are still unprotected against internal corrosion, the reported cause of 10% of significant pipeline incidents.[33] Internal corrosion is often caused by carbon dioxide in the natural gas stream, which becomes highly corrosive in the presence of water. Corrosion mitigation techniques for legacy pipelines include the introduction of corrosion inhibiters into the pipeline, reduction of moisture in the lines, and the use of robotic devices that detect corrosion failure before it becomes catastrophic. For new pipelines, it is possible to coat the inside of a steel pipeline with a corrosion-resistant coating or paint. Alternatively, a corrosion-resistant material can be selected for the entire pipeline structure. Non-metallic pipeline materials offer corrosion resistance without the need for coatings and cathodic protection. Fiberglass and polyethylene pipelines have begun entering the market due to maintenance advantages; however, adoption has been limited by the comparatively high cost of fiberglass and plastic pipelines and by their susceptibility to damage during excavation and digging.[34] Emerging solutions such as metal/plastic hybrids are also under active development.[35] Some of the most important areas for R&D, as identified by the Pipeline and Hazardous Materials Safety Administration (PHMSA), [36] include:

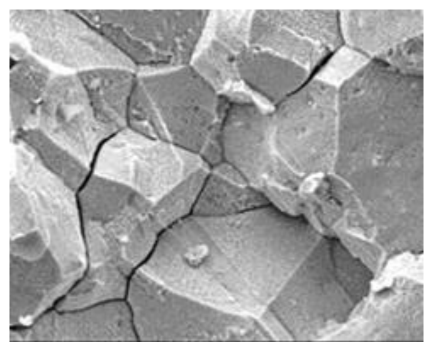
Figure 4. Hydrogen-induced embrittlement of a steel alloy's microstructure (National Institute of Standards and Technology)[37]

[28] *Gas Distribution Mains by Decade Installed,* Pipeline & Hazardous Materials Safety Administration (2014).
[29] *Public Law 90-481: Natural Gas Pipeline Safety Act of 1968.*
[30] "Significant Pipeline Incidents by Cause," Pipeline & Hazardous Materials Safety Administration (2014).
[31] R. B. Jackson, A. Down, N. G. phillips, R. C. Ackley, C. W. Cook, D. L. Plata, and K. Zhao, "Natural gas pipeline leaks across Washington, DC," Environmental Science & Technology 48 (2014) 2051-2058.
[32] EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012, available from: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf
[33] "Significant Pipeline Incidents by Cause," Pipeline & Hazardous Materials Safety Administration (2014).
[34] P. Lahey, "Use of composite materials in the transportation of natural gas," Idaho National Engineering and Environmental Laboratory (2002).
[35] P. Lahey, "Use of composite materials in the transportation of natural gas," Idaho National Engineering and Environmental Laboratory (2002).
[36] M. Baker and R. R. Fessler, *Pipeline Corrosion Final Report*, U.S. DOT Pipeline and Hazardous Materials Safety Administration (2008), available from: http://primis.phmsa.dot.gov/iim/docstr/FinalReport_PipelineCorrosion.pdf

- ***Advanced pipeline coating technologies***. Coatings must provide uniform corrosion resistance, durability to construction and handling, and the coating should be able to be applied in a mill or in the field. Thermal sprayed metallic coatings (aluminum and zinc) are emerging technologies that could provide excellent corrosion resistance at a low cost.
- ***Pipeline corrosion detection.*** Long-range guided-wave ultrasonic testing is being developed to detect metal loss in pipelines. This technique could be especially valuable in difficult-to-access locations. R&D is needed to reduce false positives from these devices and enable the calculation of failure pressures.
- ***Modeling to support direct assessment of corrosion.*** Direct corrosion assessment techniques are only effective if the locations that are most susceptible to corrosion are known. R&D is needed to understand where the likelihood of corrosion is highest, and to determine the appropriate intervals for re-assessment based on corrosion and crack growth rate modeling.
- ***Prevention of stress corrosion cracking.*** Stress corrosion cracking (SCC) is known to occur in high-pH (pH 9.0-10.5) and near-neutral (pH 6.0-7.0) environments. High-pH stress corrosion cracks are integranular (propagating along the grain boundaries) while near-neutral stress corrosion cracks are transgranular (propagating through the grains). Internal SCC is emerging as a major concern for the pipeline transport of ethanol, as SCC has been observed in ethanol storage tanks. R&D is needed to prevent internal SCC in pipelines carrying ethanol and ethanol blends, and to determine safe conditions for pipeline transport of ethanol.

Corrosion-resistant pipelines could also benefit the development of a hydrogen energy infrastructure. The storage and transportation of hydrogen fuels is complicated by the fact that structural steels are sensitive to hydrogen embrittlement and fatigue fracture (as shown in Figure 4), which can lead to hydrogen leakage. Research objectives to address the nation's needs for hydrogen-resistant pipelines overlap those for corrosion-resistant natural gas pipelines, including advanced steel and non-ferrous pipeline materials, protective coatings, and improved welding techniques.

2.3 Energy-Efficient Vehicles

The U.S. consumes more motor gasoline than any other country in the world at 9 million barrels per day, equivalent to 19 Quads annually—more than five times the consumption of China, the second largest consumer.[38] In 2012, the U.S. transportation sector released 1.8 billion metric tons of greenhouse gases (CO_2-equivalent) into the environment.[39] The use of advanced lightweight structural materials is key to improving fuel economy and reducing vehicle emissions; see [Lightweighting TA from Transportation chapter] for a detailed analysis of the impacts of lightweight materials on energy use in the transportation sector. However, lightweight alloys such as magnesium and aluminum suffer from low

[37] *Hydrogen Pipeline Material Testing Facility, National Institute of Standards*, available from: http://www.nist.gov/mml/acmd/structural_materials/hydrogen-pipeline-safety.cfm
[38] *International Energy Statistics,* U.S Energy Information Administration, available from: http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=5&pid=5&aid=2
[39] *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012,* U.S. Environmental Protection Agency (2014), available from: http://energy.gov/sites/prod/files/2014/02/f8/hdtt_roadmap_june2013.pdf

wear and corrosion resistance compared to steel, leading to short lifetimes in service. Coatings and surface modifications can be used to improve corrosion and wear resistance, enabling the use of these materials in vehicles for substantial fuel economy savings. For example, researchers in China recently showed that corrosion resistance of the AZ31 magnesium alloy could be improved by an order of magnitude by applying a hard protective coating consisting of diamond-like carbon, aluminum nitride, and aluminum layers.[40] Developments in this area will become increasingly important as Corporate Average Fuel Economy (CAFÉ) standards ramp up in coming years.

2.4 Geothermal Energy

In the U.S., geothermal energy currently accounts for 15 million megawatt-hours (0.05 Quads) of annual electricity production, with a generating capacity of 2.6 GW.[41] While geothermal represents only a small fraction of the electricity generated in the U.S. today, interest in this resource is growing as geothermal energy is a sustainable energy source with minimal environmental impacts. A recent U.S. Geological Survey assessment estimated that known geothermal systems in the U.S. have a potential capacity of 9.1 GW, and that undiscovered resources could boost geothermal capacity to 30 GW or more.[42]

A major technical barrier for geothermal power plants is that geothermal fluid is highly corrosive. Non-condensable gases (NCGs) in the steam such as dissolved carbon dioxide (CO_2) and hydrogen sulfide (H_2S) attack metals, causing stress corrosion cracking, fatigue, and other issues in geothermal equipment.[43] Further, the presence of NCGs substantially reduces power plant efficiency if not removed. Steam ejectors—the most common equipment for removing NCGs—utilize high-pressure steam from the geothermal well to compress the NCG/steam mixture and separate out the NCGs before directing the steam to the turbine.[44] Steam ejection is an energy-intensive process that utilizes large amounts of well steam which would otherwise be used to generate electricity. Conversely, mechanical pumps can be used to remove NCGs without using well steam—but mechanical solutions are limited due to poor corrosion resistance of the mechanical equipment and the high cost of large turbomachinery. R&D efforts could help overcome these barriers. For example, a U.S. start-up company showcased at the 2014 DOE National Clean Energy Business Plan Competition is now developing corrosion-resistant carbon fiber turbocompressors.[45,46] Technical advances in this area could lead to efficiency gains for

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[40] G. Wu, W. Dai, H. Zheng, and A. Wang, "Improving wear resistance and corrosion resistance of AZ31 magnesium alloy by DLC/AlN/Al coating," Surface & Coatings Technology 205 (2010) 2067-2073, available from: http://marinelab.nimte.cas.cn/archives/201312/W020140225599605306266.pdf

[41] *Renewable Energy by Fuel, United States.* Energy Information Administration: Annual Energy Outlook 2014, available from: http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2014&subject=0-AEO2014&table=67-AEO2014&region=3-0&cases=ref2014-d102413ahttp://www.eia.gov/oiaf/aeo/tablebrowser/

[42] C. F. Williams, M. J. Reed, R. H. Mariner, J. DeAngelo, and S. P. Galanis, Jr. *Assessment of moderate- and high-temperature geothermal resources of the United States.* U.S. Geological Survey Fact Sheet 2008 – 3082 (2008).

[43] T. Kaya and P. Hoshan, "Corrosion and Material Selection for Geothermal Systems." Proceedings of the World Geothermal Congress, Antalya, Turkey, 24-29 April 2005.

[44] M. Dabbour, J. Villena, R. Kirkpatrick, B. R. Young, and W. Yu, "Geothermal reboiler process development modeling." Proceedings of Chemeca 2011, New South Wales, Australia, 18-21 September 2011.

[45] "Black Pine Engineering Wins Clean Energy Trust Clean Energy Challenge," Washington, DC: DOE Office of Energy Efficiency & Renewable Energy (2014).

[46] *Black Pine Engineering: Business* Plan. Lansing, MI: Black Pine Engineering (2014).

geothermal power plants and increased utilization of this clean, sustainable resource. In addition, carry-over effects from this R&D could make an impact in the natural gas and oil drilling industries.

2.5 Nuclear Power

The U.S. nuclear fleet generates about 800 million megawatt-hours (2.7 Quads) of electricity annually and is the largest source of emission-free electricity.[47] In an aging fleet, most reactors have exceeded their planned 40-year lifetimes and are now operating under 20-year license renewals from the Nuclear Regulatory Commission (NRC).[48] The NRC expects to receive further renewal requests, extending total reactor lifetimes to 80 years, within the next five years.[49] In consideration of the extended expected lifetimes of nuclear reactors, irradiation-induced material degradation is a critical area of research. A summary of the environmental conditions expected in advanced nuclear fission reactors and (future) magnetic fusion power systems is given in **Table 6**.

Table 6. Environmental conditions expected for structural materials in advanced nuclear fission reactors and magnetic fusion power systems[50]

		Structural Materials	Maximum temperature	Maximum radiation dose	Peak steady state stresses	Chemical reactivity
Fission reactors	Commercial light water reactors	Zirconium alloys, stainless steels, Incoloy nickel-based alloys	<570°F	1 dpa	870-2175 psi (coolant pressure)	Water/steam
	Gas cooled thermal reactors	Graphite	~1830°F	1-2 dpa	2900 psi (helium pressure)	Helium gas
	Molten salt reactors	Graphite	~1830°F	1-2 dpa	145 MPa (fluoride salt pressure)	Fluoride salt
	Liquid metal cooled reactors	Martinsitic steels	<1110°F	30-100 dpa	145 psi (coolant pressure)	Sodium, lead bismuth
Magnetic fusion systems	Tritium breeding blanket and first wall	Advanced ferritic steels; vanadium alloys; silicon carbide (SiC); refractory alloys	1020–1300°F (1830°F for SiC)	150 dpa	7250 psi (electromagnetic forces)	Molten lithium/lead alloy
	Diverter system	Tungsten alloys; graphite	>1830°F	150 dpa	7250 MPa (electromagnetic forces)	none

Reactor pressure vessels are generally permanent fixtures of a facility, and must resist various modes of irradiation-induced degradation, including stress corrosion cracking, radiation creep, and swelling.[51] Fuel

[47] *Status and Outlook for Nuclear Energy in the United States,* Nuclear Energy Institute: Washington, DC (2010).
[48] *US NRC Expects Application to Extend Nuclear Licenses Beyond 60 Years,* Platts Nucleonics Week (26 February 2014)
[49] *US NRC Expects Application to Extend Nuclear Licenses Beyond 60 Years,* Platts Nucleonics Week (26 February 2014)
[50] Data Source: *Basic Research Needs for Materials under Extreme Environments,* U.S. DOE Office of Science (2007), available from: http://science.energy.gov/~/media/bes/pdf/reports/files/muee_rpt.pdf
[51] *Critical Issues Report and Roadmap for the Advanced Radiation-Resistant Materials Program,* Electric Power Research Institute (2012).

cladding is another important area for advanced materials development. Fuel assemblies, consisting of an array of zirconium-alloy-clad fuel rods, are generally retired every 18 months due to degradation of the cladding material. Given an average refueling outage of 41 days,[52] refueling outages cost U.S. nuclear plants 67 million megawatt hours of energy generation per year.[53] Since nuclear generation displaces fossil fuel generation to meet the nation's electricity needs, reduced nuclear reactor downtime can reduce U.S. greenhouse gas emissions. A 50% reduction in reactor downtime would eliminate an estimated 34.7 million tons of CO_2 from being released into the atmosphere every year.

Improved, longer-lasting cladding materials could increase the service life of fuel assemblies for increased reactor uptime, greater energy derived from the nuclear fuel, and reduced disposal of radioactive materials. Accident-resistant cladding is an emerging area of particular interest. At temperatures beyond 2200°F, zirconium alloys react exothermically with steam, producing large amounts of hydrogen and contributing to nuclear core meltdown in loss-of-coolant accidents.[54] Silicon carbide, a ceramic material with thermal stability to 4900°F and low chemical reactivity, is a candidate cladding material that may be able reduce the severity of accidents like the 2011 disaster at Fukushima.[55]

3. Program Considerations to Support R&D

3.1 Key Research Needs

Durable materials have a strong impact on national infrastructure, including pipelines and power generation plants. While private entities such as electric utilities providers and vehicle manufacturers are key stakeholders in these technologies, they lack the resources for infrastructural overhauls. Private companies may also have limited access to the analysis tools and equipment needed to develop new materials or adapt a new material to their needs. Uncertainties associated with emerging technologies also deter private industry from developing the new materials needed to advance technologies such as waste heat recovery in harsh environments, accident-tolerant nuclear fuel cladding, and ultra-supercritical steam turbines—despite the potential energy and cost savings.

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[52] *U.S. Nuclear Power Plants: General U.S. Nuclear Info*, Nuclear Energy Institute (2013), available from: http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants

[53] Based on a net nuclear energy summer capacity of 101,885 MW (2012 EIA Electric Power Annual, Table 4.3, http://www.eia.gov/electricity/annual/html/epa_04_03.html), a 41-day outage for every nuclear facility corresponds to an overall loss of (101,885 MW)*(41 days)*(24 hrs/day) = 100,225,320 megawatt-hours of electricity generation every 18 months, or a loss of 66,816,880 megawatt-hours of generation per year. Substitution of fossil fuel electricity generation for this lost nuclear generation leads to annual greenhouse gas emissions of 138,979 million lbs of CO_2, assuming 2,080 lbs of emitted CO_2 per megawatt-hour generated for bituminous coal (EIA, http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11). A 50% reduction in nuclear reactor downtime, therefore, corresponds to a 33.4 megawatt-hour annual increase in nuclear generation and a corresponding reduction of 69,489 million lbs of CO_2 emitted annually, or about 34.7 million tons.

[54] P. Hofmann, S. Hagen, G. Schanz, and A. Skokan, "Chemical Interaction of Reactor Core Materials Up to Very High Temperatures," Kernforschungszentrum Karlsruhe Report No. 4485 (1989).

[55] G. Griffith, "U.S. Department of Energy Accident Resistant SiC Clad Nuclear Fuel Development," Idaho National Laboratory Report No. INL/CON-11-23186 (2011).

Because durable materials technologies are inherently interdisciplinary, major opportunities exist for national initiatives that tie together research & development efforts across fields. Resource sharing is one key element of additionality for such efforts. For example, advanced metrology—such as *in situ* microscopy—is useful for the characterization of material behavior in extreme environments, but this equipment can be costly and in some cases is not commercially available. An investment in an advanced metrology tool could have benefits for many projects and industry partners. Similarly, modeling tools and the knowledge of subject-matter experts could be shared across applications.

3.1 Engagement Strategy

The U.S. boasts a broad network of durable materials researchers in government, industry and academic settings. However, researchers are not currently united by any one community or objective, as their research spans many applications and nearly all categories of materials. Seemingly disparate research programs can have work that overlaps quite substantially, but investigators are kept at arm's length by separate research communities and independent facilities. The result is slow transfer of technology and expertise between applications (e.g., an innovative high-temperature steel developed for a steam turbine may not immediately find itself used in a waste heat recuperator), a scarcity of shared metrology and equipment resources, and potential duplications of effort.

One potential engagement strategy is the formation of a research hub or institute, which could potentially unite the network of researchers by facilitating collaborations and industry partnerships. Germany's Fraunhofer Institute for Structural Durability—now over 75 years old—is a successful example of a government-funded research institute that has adopted an industry-partnership strategy. The Institute for Structural Durability is actively researching carbon fiber lightweighting technologies, aging effects in polymers, non-destructive evaluation techniques for aluminum castings, and other structural durability projects, and has been successful in securing 70% of its funding from contract work. A second, complementary engagement strategy involves the development of computational materials analyses to accelerate the identification of new materials based on key performance metrics for a given application. This type of activity is underway at the National Institute of Standards and Technology (NIST) in the form of a Materials Genome Initiative (MGI).[56] Specific opportunities and challenges for this type of effort as related to advanced manufacturing are explored in [Reference to MGI TA.]

3.2 Metrics

Objective metrics are needed to measure the success of any government investment. Appropriate evaluation criteria depend on technology readiness, and can be categorized by the level of the project:

- **Innovation and Feasibility Metrics.** Since physical prototypes may not yet exist at this stage, metrics for success at this level include traditional signs of productivity and direction. These could include the publication of research articles and roadmaps, and successful proof-of-concept demonstrations at the laboratory or model scale.
- **Fabrication and Validation Metrics.** At this stage, projects should demonstrate measurable increases in durability measures, such as temperature resistance or corrosion resistance.

[56] NIST, "The Materials Genome Initiative," http://www.nist.gov/mgi/

- **Scale-Up and Commercialization Readiness Metrics.** At this stage, essential metrics include technology cost reductions from improved manufacturing techniques, demonstrated energy reductions, and acceptance of the new technology in industry (competitiveness).

4. Sidebars and Case Studies

4.1 Cross-Cutting Applicability of Durable Materials

Selected Applications, Durable Material Needs, and Roadmaps	*Phase-Stable Materials*		*Functional Surfaces*		*Material Aging*	
	High-Temperature Stability	High-Pressure Stability	Corrosion Resistance	Wear Resistance	Neutron Embrittlement	Hydrogen Embrittlement
Waste Heat Recuperator	X[1]		X[1]			
Gas Transmission Pipeline		X[2]	X[2]			X[3]
Vehicle Structural Component	X[4]		X[4]	X[4]		
Nuclear Fuel Cladding	X[5]	X[5]			X[5]	X[5]
Ultra-Supercritical Turbine	X[6]	X[6]	X[6]			

1 *Energy Loss Reduction and Recovery in Industrial Systems,* U.S. DOE / EERE (2004)
2 *Interagency Research and Development Five-Year Program Plan for Pipeline Safety and Integrity,* U.S. DOT, U.S. DOE, and NIST (2007)
3 *Hydrogen Delivery Technical Team Roadmap,* U.S. DRIVE Partnership (2013)
4 *Materials Technical Team Roadmap,* U.S. DRIVE Partnership (2013)
5 *Nuclear Energy Research and Development Roadmap,* U.S. DOE / Office of Nuclear Energy (2010)
6 *High-Efficiency Coal-Fired Power Generation,* International Energy Agency (2012)